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Heterogeneous defensive naval weapon assignment to swarming threats in real-time

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THESIS

HETEROGENEOUS DEFENSIVE NAVAL WEAPON ASSIGNMENT TO SWARMING THREATS IN REAL-TIME

by

Christopher L. Laird

March 2016

Thesis Advisor:	Connor S. McLemore
Second Reader:	W. Matthew Carlyle

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HETEROGENEOUS DEFENSIVE NAVAL WEAPON ASSIGNMENT TO SWARMING THREATS IN REAL-TIME

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Submitted in partial fulfillment of the
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LIST OF ACRONYMS AND ABBREVIATIONS

AO	area of operation
ARREST	Adaptive Rapid Response to Swarming Threats
C2	command and control
CIC	combat information center
CIWS	Close-In Weapons System
CVN	U.S. Navy Aircraft Carrier
DDG	U.S. Navy Arleigh Burke destroyer
ESSM	Evolved SeaSparrow Missile
FCS	fire control system
GAMS	General Algebraic Modeling Software
GMLS	Guided Missile Launching System
GUI	graphical user interface
LCS	U.S. Navy Littoral Combat Ship
LHA/LHD	U.S. Navy Amphibious Assault Ship
LPD	U.S. Navy Amphibious Transport Dock
LSD	U.S. Navy Dock Landing Ship
MIP	mixed-integer programming
NAVAIR	Naval Air Systems Command
ONR	Office of Naval Research
RAM	Rolling Airframe Missile
SM	Standard Missile
TLAM	Tomahawk Land-Attack Missile
U.S.	United States
VBA	Microsoft Visual Basic for Applications
VLS	Vertical Launch System
WEZ	weapon engagement zone

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EXECUTIVE SUMMARY

Emerging threats to naval ships include lower-cost, unsophisticated systems that can overwhelm ship defensive capabilities when used in large numbers across multiple domains (air, surface and subsurface). There is no integrated operational system designed to allocate heterogeneous naval defensive weapons to heterogeneous, swarming threats. A defensive system capable of countering swarming threats across multiple domains will be essential for naval forces that anticipate fighting in contested, high-threat environments in the future.

The Adaptive Rapid Response to Swarming Threats (ARREST) program seeks to develop such a capability. The Office of Naval Research (ONR) and Naval Air Systems Command (NAVAIR) have proposed adapting existing Mk 49 Guided Missile Launch System to incorporate multiple effectors alongside the rolling airframe missile to address surface and subsurface threats in addition to air threats.

Pairing naval weapons to swarming threats in multiple domains with multiple defensive systems is an extremely difficult task that is currently performed manually. For the scenarios envisioned, the expected number of possible response options will involve numerous possible pairings and millions of unique order-of-engagements. We describe an automated decision aid called *Athena* that assists decision makers by providing high-quality pairing recommendations in real-time.

Athena uses a pre-processing algorithm and a mixed-integer linear programming model that provides operators with optimal defensive weapon-target pairing profiles that best use available assets in contested environments. The pre-processing algorithm takes user inputs regarding the available shipboard defense weapons, as well as the characteristics of any incoming targets. The algorithm screens the possible weapon-target pairings for feasibility based on weapon and target type (air, surface, subsurface) and weapon capabilities, such as the weapons engagement envelope and range. Additional considerations include the expected time until target impact and the time required to engage the threat. Feasible pairings are then assigned a reward value, a function of the

time available to engage the incoming threat, the priority of the threat and the probability of destroying the threat. This reward value is an indicator of the desirability of a given weapon-target pairing and is used to identify the most important threats. Additionally, the proposed model looks ahead within the scenario and reward values for feasible weapon-target pairings are calculated for the present location of the incoming threat, as well as where the threat will be at user-defined time intervals. Viewing the engagement in three distinct time periods provides the model with the ability to pair weapons and targets in the future that may not be feasible at present due to range and envelope restrictions. These reward values are then used within a mixed-integer linear programming model that works to optimally pair available weapons to targets with the objective of maximizing the total reward of the engagement profile. The results of this assignment problem are then reported to the user for further prosecution.

In a test scenario of four incoming targets to be countered with two multi-domain capable RAM launchers, the average model solve time using Microsoft Excel VBA for pre-processing and GAMS/CPLEX for the mixed-integer linear program is approximately two seconds on a general purpose laptop computer. This grows to approximately three seconds for an expanded scenario of 13 targets and four defensive weapons systems evaluating 312 unique weapon-target pairings across the three time periods.

As envisioned, this model could be operated with or without an operator-in-the-loop, depending on the systems available, expected threats, and commander's intent. In addition, this model has the potential to be implemented within a networked ship-defense environment, allowing multiple ships to share defensive systems. This networked ship defense would provide mutual support for ships defending against incoming swarm threats by optimally tasking available defensive systems in a coordinated manner. While we focus on the integration of the RAM system, the model can accommodate virtually any shipboard weapon system, including the Phalanx Close-In Weapon System (CIWS), M2 .50-caliber machine gun, Mk 45 5" deck gun and the Vertical Launch System (VLS) utilizing various Standard Missiles (SM), Tomahawk Land Attack Missiles (TLAM) and Evolved SeaSparrow Missiles (ESSM).

Implementation of this model can provide the operator the ability to quickly and efficiently respond to swarming threats, alleviating inefficient and burdensome manual processes.

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I. INTRODUCTION

A. PURPOSE AND OVERVIEW

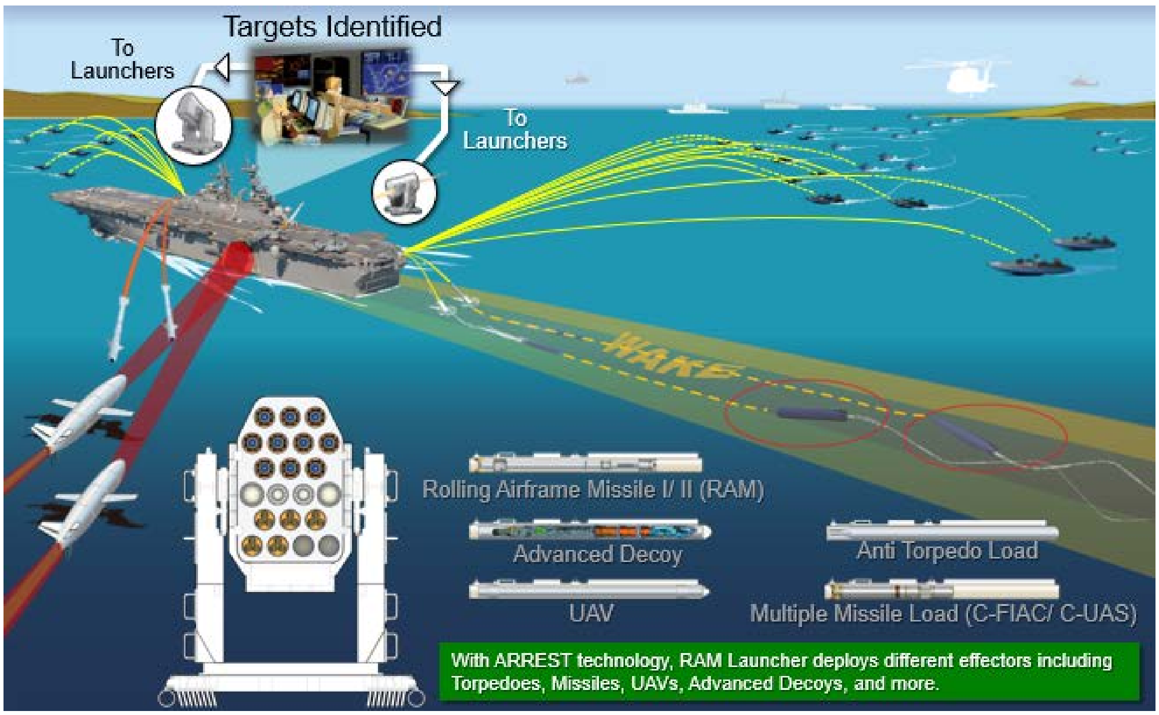
Multi-domain swarming threats are at the forefront of naval defense debates; U.S. defensive systems are vulnerable to swarming attacks that can simply overwhelm defensive capacity. Drone technology and increasingly dangerous long-range anti-ship missiles have become widely proliferated and relatively cheap. Defending naval forces against combinations of such threats is complicated. In a 2014 Office of Naval Research (ONR) media release regarding the development of unmanned surface vessels capable of autonomously conducting swarming operations, then Chief of Naval Operations Admiral Jonathan Greenert, noted that “networking unmanned platforms … is a cost-effective way to integrate many small, cheap and autonomous capabilities that can significantly improve our warfighting advantage” (p. 1). While these technologies and tactics represent new warfighting opportunities, they also present a threat to existing naval forces. As swarming technology matures, the threat it poses to ships will continue to increase, and achieving adequate defensive responses from existing manual processes will become increasingly unlikely.

ONR, with Naval Air Systems Command (NAVAIR) support, is exploring methods to counter swarming threats through the Adaptive Rapid Response to Swarming Threats (ARREST) program. Specifically, “the ability to organically engage a number of threats” is an identified and well-documented critical need across the naval forces (ARREST Technology Assessment Briefing, 2014, p. 2). The focus of the ARREST program is to develop a system capable of efficiently countering multiple threats across multiple domains. Ideally, the use of an in-service platform would reduce cost and allow for quicker fielding of the system.

Prominent shipboard defense systems currently in use in the U.S. Navy include the Rolling Airframe Missile (RAM), packaged within the Mk 49 Guided Missile Launching System (GMLS), the Close-In Weapon System (CIWS) and the Evolved SeaSparrow Missile (ESSM). ONR and NAVAIR are researching the development of the

GMLS as a multi-domain defensive system, packaging multiple effectors with the ability to counter air, surface and subsurface threats within a single platform. The GMLS is currently used in the U.S. Navy aboard carriers (CVN), large-deck amphibious ships (LHA, LHD) and smaller amphibious transport and dock ships (LPD, LSD). As seen in Figure 1, the envisioned system would allow a single defensive unit to counter multiple threats spread across multiple domains.

Figure 1. Envisioned Multi-Domain Engagement with ARREST



ARREST Multi-Domain Ship Defense System. Countering multiple threats across multiple domains presents a complex battlespace management scenario. The proposed integration of multiple effectors within the GLMS allows a single asset to counter multiple threats across multiple domains. Source: Office of Naval Research (2014). Adaptive rapid response to swarming threats concept briefing. Presented at Naval Postgraduate School, Monterey, CA.

The Navy still requires an automated decision aid that is capable of rapidly pairing defensive weapons to multiple targets operating in multiple domains so that the proposed system can be efficiently tasked. An automated system is essential as battlespace complexity and types of available weapon systems continue to grow. We propose fast pre-processing algorithms operating in conjunction with a mixed-integer programming (MIP) model for weapon-to-target assignment. With this method, weapon-target pairs can be made rapidly, allowing the operator to quickly identify the most important incoming threats and assign a defensive asset to engage. This system could be used to inform decision makers of the best available engagement profile in a highly contested environment or, in some threat environments, be allowed to automatically pair defensive systems to incoming threats for engagement without operator intervention.

We propose a solution that relies on a two-step method of pre-processing and optimization. The pre-processing step includes the input of data pertaining to the battlespace, as well as the necessary calculations required for the subsequent engagement optimization. The optimization utilizes an MIP to quickly assess the feasible response options and provides optimal weapon-target assignments given current target information and ship capabilities. This automation reduces the workload of the operator, allowing all possible response options to be considered in a much shorter time than possible with a manual process.

B. PROBLEM STATEMENT

Work within command and control (C2) stations aboard ships operating in hostile and contested areas can be overwhelming. Operators must be able to quickly orient themselves within the battlespace, assess the situation and respond to threats. With multiple incoming threats and multiple defensive options available to counter, the number of possible response options can grow rapidly and may prove too numerous to efficiently consider. In contested environments, the abilities of the operators to assess the battlespace and respond accordingly can rapidly degrade.

Currently, operators must identify the weapon-target pairings to execute over an extremely short period. These pairings must be made quickly with only the information presented by the ships' warning systems. In such situations, it is possible to overlook an important aspect of the engagement, such as the range and envelope capabilities of the weapon employed or the order in which the threats are engaged.

Ideally, the identification and prioritization of the most dangerous threats should lead to a working pairing profile; however, this process is not always straightforward.

While "dangerous" in the typical sense refers to identifying the threat most capable of damaging the ship, this may not always be the case. We must also consider the time aspects of the engagement in order to produce a hierarchical target-priority list and engage those threats that pose *immediate* danger to the ship first, not necessarily those with the highest capacity to damage.

C. THESIS ORGANIZATION

Chapter II of this thesis discusses the inherent difficulties of optimally and efficiently pairing weapons and targets in highly contested environments from the standpoint of the operator. Chapter III describes the proposed model in more detail, outlining the pre-processing algorithm and the mixed-integer programming model used to solve for the optimal engagement profile. Chapter IV illustrates the use of this model in notional test scenarios. Chapter V presents conclusions and potential future work in the advancement of this model.

D. BACKGROUND OF WEAPON PAIRING OPTIMIZATION

Much of the previous work referenced in this research was conducted to aid planners in air tasking and mission assignment. While the process of air tasking is quite different from naval ship defense, many of the critical factors involved, as well as the modeling and methodology, are applicable to shipboard defense. Of particular note is the prioritization of threats and the use of fast pre-processing algorithms and mixed-integer programming optimization.

Air-tasking operations were researched by Dolan (1993) and Crawford (1994) and resulted in automated and optimized pairing recommendations. Their work included target prioritization and pairing recommendations that quickly assessed a static environment and enabled tasking optimization in advance of execution. Castro (2002) went on to develop an optimization tool that allowed for the handling of time-sensitive targets within the air-tasking environment. Research done by Weaver (2004) continued the development of previous models and determined that a decrease in the model runtime was necessary for future operations. Follow-on research by Zacherl (2006) focused on speeding up this processing time and developed the Rapid Asset Pairing Tool-Operations Research (RAPT-OR) model.

More recent work by McLemore (2010) and Albrecht (2015) extended and increased the fidelity of the RAPT-OR model for use by C2 operators, providing mission pairing profiles in real time. Both McLemore (2010) and Albrecht (2015) employ reward-based mixed-integer programming models used to identify the most effective and efficient use of air assets based on weapon, target and timing criteria. This method of producing optimal weapon-target pairing is at the heart of this thesis, as a reward-based MIP organically produces a hierarchical output of weapon-target pairings, thereby identifying the most critical threats posed to a ship in a defensive situation.

E. SCOPE AND LIMITATIONS

This thesis is intended to formalize the mathematical implementation of an automated weapon-target pairing model for use in shipboard defense scenarios. The focus of this research is to illustrate the approach to solving such scenarios, as well as demonstrating the model's capabilities. The model developed within this work highlights the pre-processing algorithms required to assess the battlespace, as well as the formulation of a mixed-integer programming model to provide weapon-target recommendations to the operator for a situation.

While this thesis proposes an automated system designed to provide decision makers with a planning tool, without extensive systems integration, it is limited by the information available for use. All inputs required for the model to be fully implemented are required to be manually entered by the user given the lack of tie-in with a functioning radar and fire-control system. This includes all weapon and target characteristics, as well as the ship heading and speed. As such, it is a stand-alone demonstration model of a future naval capability and would require extensive integration with shipboard systems to produce a working defensive system.

In addition, all of the system data used within the thesis was obtained from open sources and is unclassified. Thus, it is only an approximation of the actual capabilities of the systems described. However, the underlying mathematical formulation is relevant; any data within the model can be easily adapted.

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II. WEAPON-TO-THREAT PAIRING IN CONTESTED ENVIRONMENTS

A. CURRENT OPERATIONS

There is no existing automated C2 process that provides coordinated heterogeneous weapon pairing recommendations for swarming threats. Currently, combat information center (CIC) operators tasked with defending the ship receive target information from the ship's radar and fire control systems, including weapon-target pairing recommendations for engagement of incoming threats. Such systems generally rely on a time-based interpretation of what threats pose the most immediate risk to the ship, identifying those with the least amount of time until impact as the highest priority. When the system is used in a man-in-the-loop mode, operators are provided with a recommended weapon-target pairing indicating which defensive weapon system should be used to counter the incoming threat, which the operator can then approve for prosecution. Operators also have the option of placing the system in an automatic engagement mode, thereby allowing the system to track and engage incoming threats without operator intervention.

The shortfalls of the current system lie in the isolated nature of the weapons involved. Current defensive systems are limited in what weapon-target pairings are considered, as the separate weapon systems do not communicate with each other. Defensive systems are paired to targets within a vacuum with little consideration for the overall optimal defensive engagement profile, instead focusing on the first available response for the most time-critical threat.

Additionally, current systems do not accurately account for multi-domain capabilities within a single defensive unit. The addition of these multi-domain capabilities within the RAM launcher, and any extension of the optimization to other defensive systems aboard the ship, presents the system and operator with many choices for countering an incoming threat. In these situations, manually selecting a feasible response, as opposed to calculating the most effective response, is unlikely to produce a high-quality defense solution for the ship. We propose an optimization model that accounts for all possible weapon-target pairings, even those that are currently infeasible but may become an option in the near future, that incorporates multiple systems with multi-domain capabilities. This model provides operators with an optimized engagement profile across all domains and available weapon systems.

B. CHALLENGES IN PROPOSED FUTURE OPERATIONS

A scenario where a ship encounters multiple threats simultaneously, each potentially requiring a different counter-munition, could result in even experienced operators becoming overwhelmed. In these situations, it would be easy to simply throw all available resources at the threat; however, this is most likely not efficient and may not even counter all threats within the battlespace. In time-sensitive defensive scenarios, the decision-maker must quickly identify the most dangerous threat and formulate an effective response, a task that can become unmanageable given the number of available alternatives.

Additionally, shipboard defense is an extremely time-sensitive operation. For example, an anti-ship missile with a maximum speed of Mach 2 (~700 m/s) launched from 5 nautical miles (~10,000 m) leaves the operator with approximately 15 seconds to decide on and execute an appropriate response. Couple this with the possibility of multiple threats being launched simultaneously and the time available to assess and decide quickly decreases.

This section outlines the key operational issues of executing defensive engagements in these highly contested environments, as well as some of the advantages of automating the process to the operator decision-making.

1. Multi-Domain Swarming Threats

For the scenarios envisioned, it is assumed that a ship could come under fire from multiple sources simultaneously. These threats would be engaged in a numbers game, seeking to saturate the battlespace with many targets in the hope that the ship’s defensive systems become so overwhelmed that they cannot defeat all incoming threats. As previously noted, ONR is already conducting its own research into offensive swarming through the use of autonomous fast-attack boats. ONR research employed 13 autonomous fast-attack boats during a live demonstration (Office of Naval Research [ONR] Media Release, 2014, p. 1).

Saturating the battlespace with enough targets to overwhelm a ship’s defensive capabilities will become an increasingly common tactic, as it is likely that the operators in existing systems can be overwhelmed. The time from detection to engagement, the pairings chosen by the operator, as well as the order in which the threats are engaged, can determine the success or failure of the engagement. As noted before, the time constraints associated with an engagement can be limiting, even for a modest number of threats. The ability of the operator to assess and decide is a critical element for the success of the engagement.

Additionally, there is no guarantee that swarming threats will be operated within a single domain (i.e. air, surface or subsurface). Hostile naval attacks of the future will likely employ forces across multiple domains, requiring a coordinated effort of defensive measures. Naval shipboard defensive systems will be required to prosecute multiple threats, including air, surface and subsurface threats simultaneously. This over-saturated battlespace must be quickly and accurately evaluated before any defensive action can be taken.

Lastly, many threats carry their own offensive capabilities. Attack aircraft and fast-attack surface craft carry secondary weapons. These secondary weapons must be taken into account in any defensive engagement, as allowing one of these incoming targets to close within firing range of the ship means the threats has effectively multiplied, with one threat becoming multiple threats. With this in mind, it is important to consider these secondary capabilities within the battlespace in order to formulate a defensive engagement profile that prevents these incoming targets from closing within firing range of the ship.

2. Multiple Defensive Systems

In addition to the number of threats to the ship, a multitude of response options must also be accounted for, and may complicate the decision-making process. For example, a simple scenario of just 3 incoming threats engaged by two distinct weapon systems leaves the operator with 6 unique pairing options to consider. This is not an extraordinary number of choices in itself, however, when ordering is considered, this number becomes 120 pairing options. In this scenario the operator must quickly identify and exclude any infeasible pairings before considering any viable response plan. In an expanded scenario of 13 incoming targets and 4 weapon systems available, similar to the demonstration conducted by ONR in 2014, the number of unique pairing options grows to 52, while the set of unique weapon-target pairings to address all threats grows to more than 600 billion, even when order-of-engagement is ignored.

The number of response options are too numerous for an operator to consider in a short time in high-stress situations. Additionally, there are other considerations; the available ammunition within each defensive system, the engagement envelope and range of the defensive system and the type of munitions available within each. Pairing weapons and targets without including all of these considerations will almost certainly result in sub-optimal pairings.

In addition to considering the feasibility of each potential pairing based on range and weapon envelope, the operator must also account for the available munitions within each weapon system. ONR has envisioned modifying the existing RAM launchers to incorporate surface and subsurface capable munitions. The introduction of additional munitions within a single unit further complicates the decision process. The current RAM system includes 21 individual launch tubes. The proposed surface munition would include 3 munitions within a single launch tube. If equally loaded with air, surface and subsurface munitions, a single unit would contain 35 munitions, leaving the operator to track 70 munitions across both available RAM systems.

While experience can certainly offer some insight into the proper response, it is sometimes difficult to create even a feasible engagement profile in high-stress environments and an automated system would be valuable.

C. ADVANTAGES OF AN AUTOMATED DECISION AID

We propose utilizing an automated decision-making process to account for the important factors in a defensive naval engagement, identify the feasible pairings and choose the optimal defense profile.

In practice, such a system would be capable of accounting for important factors within an engagement, including availability of defensive weapons and incoming target information. This system could be used to provide a recommendation to the operator on the optimal defensive engagement profile given the current situation. When needed, this system could also operate in a fully automatic mode that allows the system to assign weapon assets to incoming targets and immediately send the targeting information weapon system for prosecution.

1. Tactical Decision Aid for Operators

While the potential for automatic engagement of incoming threats is a valuable tool in high-threat environments, it may not always be the preferred method of operation. Factors such as battlespace complexity, mission, expected threats and commander's intent will all play a role in deciding the mode of engagement and may not allow for the use of a fully automatic defense system.

The previously mentioned factors will play an important role in the method of operation of any ship defense system. These factors will dictate whether the system should be used as a planning tool or a fully automated defense system. Keeping the operator in the decision making process will be extremely useful in almost all cases due to the large number of non-hostile vessels transiting many of today's operating areas. Keeping the operator as the final approval authority in the kill-chain decreases the likelihood of mistaking a friendly or neutral vessel as hostile. Additionally, while warships must always be ready to respond to a threat, today's operations are not conducted with the expectation of being overtly attacked by a large force as they would in a time of war.

In these cases, having an operator in the loop to make critical decisions regarding the defense of the ship may be preferred. With an operator in the loop, the battlespace would be assessed by the ship's combat systems and processed accordingly. Once the best available engagement profile has been identified, the operator would be provided with the optimal weapon-target pairings for further adjudication and tasking. While this method may not be as fast and efficient as the fully automatic mode, it does have the advantage of keeping the operator in the decision-making process, and is especially useful in situations of restricted combat when contacts within the battlespace are considered to be non-threats. In such an environment it is important to allow the operator to make the final determination on whether a target is a threat and should be prosecuted. In this case any recommendations provided by the *Athena* model could be pre-loaded into the ship's fire control system, ready to be tasked pending operator approval in a manner that is similar to current procedures. This recommendation can be provided to the operator within 1–2 seconds for most scenarios allowing the operator to quickly prosecute the engagement.

2. Fully Automatic Pairing and Engagement

In cases where the battlespace warrants an automatic engagement mode, this model could be used as a quick and efficient means of identifying the optimal engagement profile and immediately pass weapon-target pairings on to the ship's fire control systems. Situations that may dictate the use of an automatic engagement mode are those in which a high number of hostile threats are overwhelming the defending force. Most, if not all, actors in the area of operations (AO) would be considered hostile and the threat of collateral damage to surface and air traffic would be minimal. AO's in which all contacts are considered hostile, such as in unrestricted warfare scenarios, would create extremely dense threat environments in which the time to assess, decide and engage threats would be greatly reduced. Environments meeting these criteria could employ an automatic pairing and engagement system to shorten the kill-chain and thereby increase the survivability of the ship.

This fully automatic mode of operation would allow the ship's defensive systems to automatically detect, track and engage incoming threats without operator intervention and would be most useful in extreme circumstances, such as when the ship defenses are overwhelmed by the number of incoming threats. In these situations, the response time and decision making of the operator can become a weak-link. Removing the burden of requiring an operator to contemplate numerous defensive options would allow the system to automatically choose the best available defensive options for the unfolding scenario in real-time and respond accordingly. This method of operation would greatly reduce the engagement timeline, from detection to execution, potentially allowing the system to respond to more threats than would otherwise be possible with human intervention. This operating mode also has the advantage of potentially freeing up operators to focus on other mission-critical tasks.

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III. NAVAL WEAPON ASSIGNMENT MODEL FOR DYNAMIC HIGH-THREAT ENVIRONMENTS

A. INTRODUCTION

This chapter outlines the *Athena* weapon-assignment system, including the inputs and outputs, pre-processing and mixed-integer programming (MIP) model required to formulate and recommend a defensive response to a given threat scenario. The system is comprised of two parts: a pre-processing algorithm to properly prepare the necessary data and MIP formulation to generate optimal weapon-target pairings.

B. MODEL ASSUMPTIONS

Some assumptions must be made in order to implement a demonstration model within the framework of this thesis. The largest assumption made in this regard is that the information used in the model inputs are, or would be, available to be passed to the model by shipboard systems. This includes a classification of the threat (air, surface, subsurface), a calculation of the target's probability of hitting the ship, its threat classification (i.e., low, medium, high or non-threat) and any secondary weapon capabilities. These parameters are critical to the prioritization of targets within the model and must be included in order to identify an optimal engagement profile. While these are extremely important characteristics for the model to consider, in the event that shipboard systems cannot provide them in real-time, they could be hard-coded into the system with minimal impact. For example, different target types could be modeled with type-based parameters such that all targets within a certain type-class would automatically be assigned parameters associated with that type (i.e., all surface craft would be assigned a medium threat level with secondary weapon capability). This would alleviate some of the burden of identifying the incoming targets individualized parameters while still giving the model an accurate picture of the unfolding scenario.

Another assumption made in the demonstration of this model is that all weapon-target pairings result in the elimination of the incoming threat and no follow-on pairings are required. While this assumption is not necessarily valid, it is also not critical, as real-world implementation of this system would result in continuous target updates. In this case, as long as the target appears within the battlespace it will be considered for pairing within each model execution. This continuous pairing consideration would allow for follow-on shots to be executed in the event that the initial engagement was not successful.

C. ASSET-TO-THREAT ASSIGNMENT MODEL

We formulate the weapon-target assignment problem as an integer linear program with the following sets, parameters, variables and constraints.

1. Sets

$w \in W$	Weapon system, identified by its name
$l \in L$	Launchers available for use on weapon system
$s \in S$	Subsystems available for use in launchers
$t \in T$	Target identification
$p \in P$	Time Period
$(w,l,s,t,p) \in A \subseteq W \times L \times S \times T \times P$	Assignment tuple representing a weapon *w* utilizing launcher *l* with subsystem *s* against target *t* in time period *p*, corresponding to a feasible pairing.

2. Parameters

$reward_{w,l,s,t,p}$	Reward value for pairing weapon w, launcher l and subsystem s to target t in time period p
$weap\_avail_{w,l,s}$	Ammunition available for weapon *w*, launcher *l* and subsystem *s*

3. Decision Variables

$ASSIGN_{w,l,s,t,p}$ — Binary Variable; 1 if weapon system *w* is utilizing launcher *l* and subsystem *s* is assigned to engage target *t* in period *p*; 0 otherwise

4. Formulation

$$\underset{ASSIGN_{w,l,s,t,p}}{\text{MAX}} \sum_{(w,l,s.t,p)\in A} reward_{w,l,s,t,p} \times ASSIGN_{w,l,s,t,p} \tag{3.1}$$

$$\sum_{p} ASSIGN_{w,l,s,t,p} \leq 1, \qquad \forall (w,l,s,t) \in \mathrm{A} \tag{3.2}$$

$$\sum_{(w,l,s,p)\in \mathrm{A}} ASSIGN_{w,l,s,t,p} \leq 1 \qquad \forall t \tag{3.3}$$

$$\sum_{t,p} ASSIGN_{w,l,s,t,p} \leq weap\_avail_{w,l,s} \qquad \forall (w,l,s) \in A \tag{3.4}$$

$$ASSIGN_{w,l,s,t,p} \in 0,1 \qquad \forall (w,l,s,t,p) \in \mathrm{A} \tag{3.5}$$

5. Formulation Discussion

Equation (3.1), the objective function, employs the model to maximize the total reward by choice of the binary variable $ASSIGN_{w,l,s,t,p}$. Equations (3.2) through (3.5) represent the constraints placed on the model in the assignment process. Equation (3.2) allows the model to make each unique weapon-target pairing only once across all time periods and prevents the model from repeatedly making the same pairing in multiple time periods. Equation (3.3) constrains the model to pairing each target only once, preventing the model from pairing multiple assets to the same target which, if allowed, could lead to other threats not being addressed. Equation (3.4) only allows pairings to be made if there is ammunition available within the assigned weapon system and equation (3.5) constrains the decision variable, $ASSIGN_{w,l,s,t,p}$, to be binary. The binary nature of the $ASSIGN_{w,l,s,t,p}$ variable serves to clearly identify which pairings are made and allows the model to calculate the overall reward for the engagement.

D. PRE-PROCESSING

The feature of our model that guides the pairing decisions is the set of $reward_{w,l,s,t,p}$ coefficients. Calculating these rewards requires pre-processing of all of the scenario data. The pre-processing algorithm used in this model takes static inputs from the Microsoft Excel user interface to conduct all pre-processing functions, including data input, feasibility checks and reward value calculations for the considered weapon-target pairings. The following subsections describe the major functions of the pre-processing algorithm.

1. Inputs

Inputs are required for all incoming targets, the current status of the ship and available weapon systems. These inputs are used to calculate the critical parameters for the prioritization of targets and feasibility of weapon-target pairings. Required inputs and their units are highlighted below:

a. Ship Characteristics

$ship\_heading_w$	Heading of weapon system *w* [degrees true]
$ship\_speed_w$	Speed of weapon system *w* [knots]

b. Weapon System Characteristics

$mission\_type_{w,l,s}$	Mission type of weapon system *w* and launcher *l* utilizing asset *s* [Air, Surface, Subsurface]
$weap\_avail_{w,l,s}$	Number of weapons in weapon system *w*, launcher *l* and subsystem *s* [number]
$weap\_range_{w,l,s}$	Maximum engagement range of weapon system *w* utilizing launcher *l* and subsystem *s* [meters]
$weap\_speed_{w,l,s}$	Speed of subsystem *s* fired from weapon system *w* and launcher *l* [meters/second]
$weap\_env_{w,l,s}$	Engagement envelope of weapon system *w* utilizing launcher *l* and subsystem *s* [degrees relative]

$weap\_swing_{w,l}$	Maximum swing rate of weapon system *w* using launcher *l* [degrees/second]
$weap\_pkill_s$	Probability of kill for weapon subsystem *s* [probability]

c. Target Characteristics

$target\_type_t$	Mission type required by target *t* [Air, Surface, Subsurface]
$target\_speed_t$	Speed of target *t* [meters/second]
$target\_range_t$	Range of target *t* [meters]
$target\_bearing_t$	Bearing of target *t* [degrees relative]
$target\_heading_t$	Heading of target *t* [degrees true]
$target\_threat_t$	Damage potential of target *t* if it hits the ship [integer from 0 to 3]
$target\_phit_t$	Probability that target *t* hits the ship [probability]

d. Secondary Weapon Systems

sec_range_t	Firing range of secondary weapon systems on target *t* [meters]
sec_threat_t	Damage potential of secondary weapon systems on target *t* [integer]
sec_phit_t	Probability that secondary weapon systems launched from target *t* hit the ship [probability]

2. Time Periods

This model allows engagements to be viewed in multiple discrete time periods to facilitate the planning process. Viewing the engagement in discrete, user-defined intervals allows the model to "plan ahead" for targets that may be outside of the weapon engagement envelope based on bearing or range at the outset of the model run. This also allows the system to naturally provide secondary and tertiary target options for operator consideration.

With this feature, the model not only considers the current state of the battlespace, but also looks ahead to determine where the ship and targets will be at the outset of the next time interval based on current course and speed. These intervals are user-adjustable, providing flexibility to the operator to adjust the look-ahead time based on expected engagement timelines. Approaching the scenario in this manner allows the model to consider engaging targets immediately or wait for a later time period, as well as allowing for the pairing of targets that are currently infeasible but may become feasible at a later time. This future pairing availability gives the operator a more accurate picture of the unfolding engagement and allows them the option to immediately task a weapon to a target or wait to engage in favor of another, more urgent threat. It also increases the operator's situational awareness and provides a clearer picture of the unfolding scenario.

Targets within the model may also be "passed off" between available weapon systems based on their position at the start of each time period (i.e., entering and leaving weapon envelopes). This opens up the model to consider additional weapon-target pairings across all time periods and effectively choose the pairing and time-period combination that is most advantageous.

3. Feasibility

Once the model inputs have been captured, the model conducts an initial feasibility check. For each weapon-target pairing considered, weapon and target types (i.e., air, surface, subsurface) are compared and, if matched, the algorithm proceeds with the necessary calculations.

Additional feasibility checks for the weapon envelopes are conducted throughout the pre-processing algorithm. For each time period considered a check is conducted to determine whether the target currently resides within the weapon envelope. Targets falling outside of weapon envelopes are considered infeasible and are immediately assigned a reward value of zero. These weapon engagement zone (WEZ) feasibility checks are conducted for each weapon-target pairing and time period considered within the engagement.

4. Timing Calculations

Concurrent to the feasibility checks, multiple timing-based calculations are executed. These calculations identify the time available and time required to engage the incoming threat and serve to identify to the most imminent threats to the ship.

First, a time-until-impact is calculated for the considered target using its closing speed. This calculation is used to represent the time available to engage the threat before it hits the ship. In the case of targets with secondary weapon systems capable of firing on the ship, the time until the target is within firing range is also calculated and the shorter of the two times is used in the reward calculation. The firing range for secondary capabilities can be target-specific or, in some cases, be user-defined, allowing the operator to set the minimum distance that threats should be allowed to approach.

Additionally, the time to fire at and intercept the threat is calculated using the available weapon characteristics. The time-to-fire calculation is concerned with how long it will take the weapon system to get into position to fire at the incoming target and is based on the current heading of the weapon system, the bearing to the target and how quickly the weapon system can be traversed to the appropriate heading. Additionally, the time for the effector to intercept the incoming target is calculated using the closing speed between the target and the effector, were it fired immediately.

The difference in these two calculations is then used to calculate the time available to engage the threat and is subsequently used as a critical parameter the reward value for each pairing, where those pairings with less time available earn more reward.

Pseudo-code for all pre-processing feasibility controls and calculations is outlined in Figure 2.

Figure 2. Pre-Processing Pseudocode

```
get weapon inputs
get target inputs
for each target
    for each weapon
        if weapon type = target type then
            calculate closing speed of target
            calculate range, bearing and p_kill for all time intervals
            for each time period
                if target within weapon envelope then
                    calculate time available and time required to engage
                    calculate reward
                else
                    infeasible pairing
                end if
            next period
        else
            infeasible pairing
        end if
    next weapon
next target
```

Pre-processing pseudocode for the *Athena* model. This pseudocode outlines the feasibility controls and important calculations required for solving the model. If a pairing is feasible within any given time period, its reward value is calculated for use in the mixed-integer programming model to determine the optimal weapon-target assignment profile. If a pairing is infeasible within a given time period, it is discarded and the pairing feasibility in the next period is assessed. This is done for all weapon-target pairs that are of the same type (i.e., air-air, surface-surface, subsurface-subsurface).

5. Calculated Data

In addition to the well-defined calculations required, such as the closing speed of the target and the time until impact, additional parameters are constructed to aid in the execution of the model. Parameters indicating the priority of the target, and the probability of successfully destroying it, are required to properly calculate the reward value for the pairing. These parameters are calculated as follows:

$$priority_t = 10 \times target\_threat_t^3 \times target\_phit_t \tag{3.1}$$

$$sec\_priority_t = 10 \times sec\_threat_t^3 \times sec\_phit_t \tag{3.2}$$

$$p\_kill_{w,l,s,t,p} = e^{(-0.25*\frac{target\_range_{t,p}}{weap\_range_{w,l,s}})} \quad (3.3)$$

The calculated parameters are subsequently used in the MIP reward function and serve to aid in the prioritization of incoming threats. Equation (3.1) sets the priority of the incoming threat according to its threat level and probability of hitting of the ship. Equation (3.2) the same as equation (3.1), but is instead a function of the secondary weapon capabilities of the incoming threat. These equations weight the threat of the target heavily, thereby encouraging the model to assign weapons to the most dangerous threats first. Equation (3.3) is used to vary the probability of successfully killing an incoming threat, instead of utilizing a single probability of kill for a given weapon system. The probability of kill is a function of the maximum range of the weapon system and the range of the target during a given time period, resulting in a value between .78 and 1.

6. Reward Value

The reward function utilized in this model is adapted from previous work in air mission tasking conducted by McLemore (2010) and Albrecht (2015). Their work developed and refined pairing reward values dependent upon target priority, probability of kill, number of weapons and targets and the time available and required to conduct the air mission. A similar methodology is used here, with minor deviations.

The reward value calculated for pairings within this model are a function of the target's priority, the probability of kill of the defensive launcher and subsystem against that target and the amount of time required and available to engage the target. In cases where the target's secondary weapon systems are the main threat to the ship the reward function is largely unchanged, the only difference being the priority value used within the calculation. The reward value function is outlined in equation (3.4).

$$reward_{w,\mathrm{l,s},t,p} = (priority_t) \times (prob\_kill_{w,\mathrm{l,s,t,p}}) \times (100 \times e^{-0.025*freetime_{w,l,s,t,p}}) \times \frac{1}{p} \quad (3.4)$$

The first term is the priority of the incoming target and is used to lend weight to those targets that are deemed to have the highest potential for damage to the ship. For example, torpedoes or high-speed anti-ship missiles have the ability to significantly degrade a ship if a successful hit occurs, while small arms aboard a patrol craft have little chance of degrading the ship if not engaged; this value allows the model to prioritize the highest threats and results in a value between 0 and 270. The second term allows for the prioritization of targets based on the expected probability of successfully engaging and destroying the threat. This value, between .78 and 1, is a function of the weapon systems maximum range and is calculated for each feasible pairing within a given time period. The third term is a function of the *freetime* variable, which is the difference between the time available and time required to engage an incoming threat. This term allows the prioritization of those targets that pose the most immediate threat to the ship and carries a value between 0 and 100. The final term of the reward function serves as a penalty for pairing targets in later time periods. Dividing by the time period in which the pairing is considered (i.e., period 1, no penalty; period 2, divide total reward by 2 etc.) encourages the model to make weapon-target pairings earlier in the scenario instead of waiting until the last second to gain as much as reward as possible during the MIP operation. The sum of these four terms is then used as the total reward value for pairing a weapon to a target within a particular period.

Reward values calculated for all feasible weapon-target pairings identify the most urgent threats to the ship and serve to naturally prioritize them, alleviating the computational burden of enumerating all possible orders of engagement. The total reward value is a number between 0 and 27,000, with higher reward values representing more desirable pairings. The reward value has little meaning in itself, however, its value relative to other pairing options is important. Only weapon-target pairings with a reward value greater than a user-specified cutoff value are included in the subsequent MIP formulation. This prevents the model from assigning pairings with extremely low reward values due to low probability of successfully neutralizing a threat, low threat priority or extremely long time-to-impact, and is useful as an ammunition-saving measure.

IV. COMPUTATIONAL RESULTS

A limited test scenario was constructed in order to demonstrate how the model pairs available weapon systems and targets. In addition, expanded and stressed test scenarios were conducted in order to verify the model's ability to handle larger and more complicated threat profiles, as well as determine the time required to solve the scenarios. All scenarios were carried out on an Asus general-purpose laptop operating Windows 10 Home Edition with an Intel Core i3-5010 @ 2.10GHz.

A. MODEL IMPLEMENTATION

The *Athena* front-end uses Microsoft Excel for user-interface and pre-processing. Microsoft Visual Basic for Applications (VBA) code is used to pre-process all input data and calculations required for the model, formulate the MIP and report the optimal pairings to the user. We use the free SolverStudio extension to connect our Excel user interface to the optimization model and solver.

The *Athena* optimization model was implemented utilizing the General Algebraic Modeling System (GAMS) modeling language with the CPLEX solver. GAMS software consists of a language compiler and integrated solvers for mathematical programming and optimization and both requires a license for full functionality. When used with the SolverStudio extension, all input data is calculated and loaded within the Excel environment, at which point an output file is compiled and passed over to the GAMS software for solving and, once complete, the results are passed back to the Excel environment. This allows the user to complete the entire process within a single user environment, without switching between software or constructing software-specific input and output files.

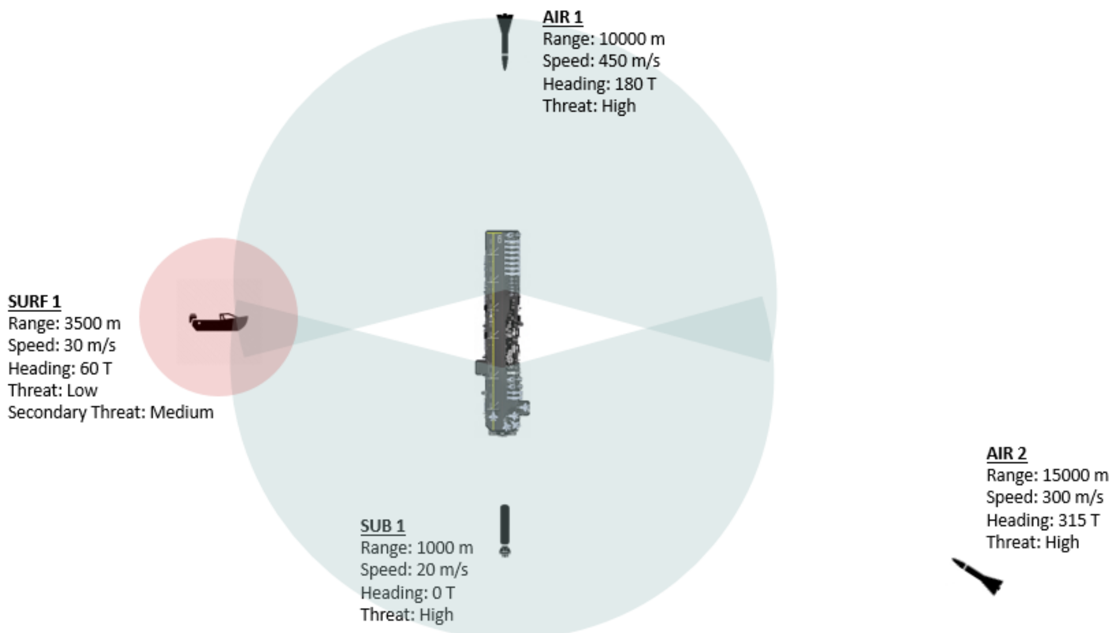
While the GAMS/CPLEX combination requires expensive licenses, there are other modeling languages and solvers available for use within the environment that are free. In order to alleviate the licensing requirements during the research phase of this thesis and allow a wider distribution, the model was also implemented in the Pyomo modeling language with the COIN-OR Branch & Cut (CBC) solver. Pyomo is an optimization extension that uses the Python modeling language.

B. TEST SCENARIO

The following test scenario was developed to validate the models automated calculations and pairing assignments. In this scenario a large-deck amphibious assault ship is steaming north at 15 knots and is faced with multiple threats in multiple domains simultaneously. This scenario depicts a ship encountering four threats spread across the air, surface and subsurface domains as shown in Figure 3.

The defensive systems available for use on the ship include two RAM launchers loaded with surface-to-air, surface-to-surface and surface-to-subsurface munitions. To model this multi-domain capability within the optimization, each RAM system is subdivided into its component munitions and is modeled as a unique, standalone system. For example, in this scenario each RAM launcher is input three times, each with a different *Type* variable to indicate its intended mission, representative of what munition is being modeled. This allows the system to treat each munition as an individual entity, as well as allows for the input of munition-specific weapon characteristics.

Figure 3. Visual Depiction of Test Scenario



Test Scenario Visualization. In this scenario, a large-deck amphibious assault ship is confronted with incoming targets spread across air, surface and subsurface domains. The red circle around the surface target is representative of secondary weapon system firing range, while the blue regions indicate the operating envelope of the ship's defensive systems. Ranges are not to scale.

All weapon characteristics are contained within a dedicated tab in the Excel GUI and includes ammunition available, range, speed and envelope inputs as shown in Table 1. Target characteristics, including range, speed, heading, threat and probability of hit, as well as information regarding secondary weapon capabilities are included within the model in the form of static data inputs as shown in Table 2. These tables are screen captures from the Excel GUI used to provide inputs to the *Athena* model.

Table 1. Test Scenario Weapon Inputs

Launcher	Submunition	Type	Num Avail	Range (m)	Speed (m/s)	Weap_Heading (degRel)	SwingRate (deg/s)	EnvelopeLo (degRel)	EnvelopeHi (degRel)
RAM1	BlockI	Air	2	15000	700	0	90	260	100
RAM1	Medusa	Surface	2	12000	700	0	90	260	100
RAM1	ATT	Sub	2	10000	30	0	90	260	100
RAM2	BlockI	Air	2	15000	700	180	90	80	280
RAM2	Medusa	Surface	2	12000	700	180	90	80	280
RAM2	ATT	Sub	2	10000	30	180	90	80	280

Test Scenario Weapon Inputs. Static weapon system characteristics tab within the model. This table contains the characteristics of the available defensive weapon systems within this test scenario, including the weapon identification, type, available ammunition and capabilities.

Table 2. Test Scenario Target Inputs

Primary Weapon System								Secondary Weapon System		
ID	Type	Range (m)	Speed (m/s)	Bearing (deg)	Heading(deg)	P_Hit	Threat	FireRange (m)	P_Hit	Damage
Air1	Air	10000	450	0	180	0.9	3	0	0	0
Sub1	Sub	1000	20	180	0	0.9	3	0	0	0
Surf1	Surface	3500	35	270	90	1	0	2000	0.8	2
Air2	Air	15000	300	135	315	0.9	3	0	0	0

Test Scenario Target Inputs. Static target characteristics tab within the model. This table contains the characteristics of each identified target, including its type, range, bearing and threat index. Targets carrying secondary weapons, such as *Surf1*, also require inputs regarding the capabilities of the secondary weapon system.

Once the ship, weapon and target characteristics are loaded into the Excel user interface the scenario can be run. The first task to be executed is the pre-processing calculations required to assign a reward value to each pairing. During pre-processing, weapon-target pairings are screened for feasibility and the set of possible pairings is reduced from 72 to 11 feasible pairings across all time periods based on weapon-target compatibility, weapon range and weapon envelope.

These feasible pairings and associated reward values are then populated into the mixed-integer programming model, as seen in Table 3. This formulation is used to assign weapon-target pairings by varying the binary decision variable *ASSIGN*. The assignment of this variable is determined by identifying the combination of pairings that maximizes the total reward of the optimization while satisfying all constraints. The recommended pairings for the outlined test scenario is shown in Table 4.

Table 3. Test Scenario MIP

Launcher	Munition	Target	Period	Reward	Assigned
RAM1	BlockI	Air1	1	11913	1
RAM2	BlockI	Air2	2	6577	1
RAM2	BlockI	Air2	1	5365	0
RAM2	ATT	Sub1	3	4717	1
RAM2	ATT	Sub1	2	3311	0
RAM2	ATT	Sub1	1	3100	0
RAM1	Medusa	Surf1	2	2205	1
RAM2	Medusa	Surf1	2	2205	0
RAM2	Medusa	Surf1	3	2072	0
RAM1	Medusa	Surf1	1	2038	0
RAM2	Medusa	Surf1	1	2038	0

Test Scenario MIP Formulation. Feasible weapon-target pairings are shown with their respective reward values. Each row represents a combination of weapon, munition, target and time period to be considered within the MIP model. The *Assigned* column is used as the decision variable within the MIP, and is assigned a binary value to indicate whether the assignment is made (1 if assigned, 0 otherwise).

Table 4. Test Scenario Assignment Report

Period 1		
Order	RAM1	RAM2
1	Air1	--
2	--	--
3	--	--
4	--	--

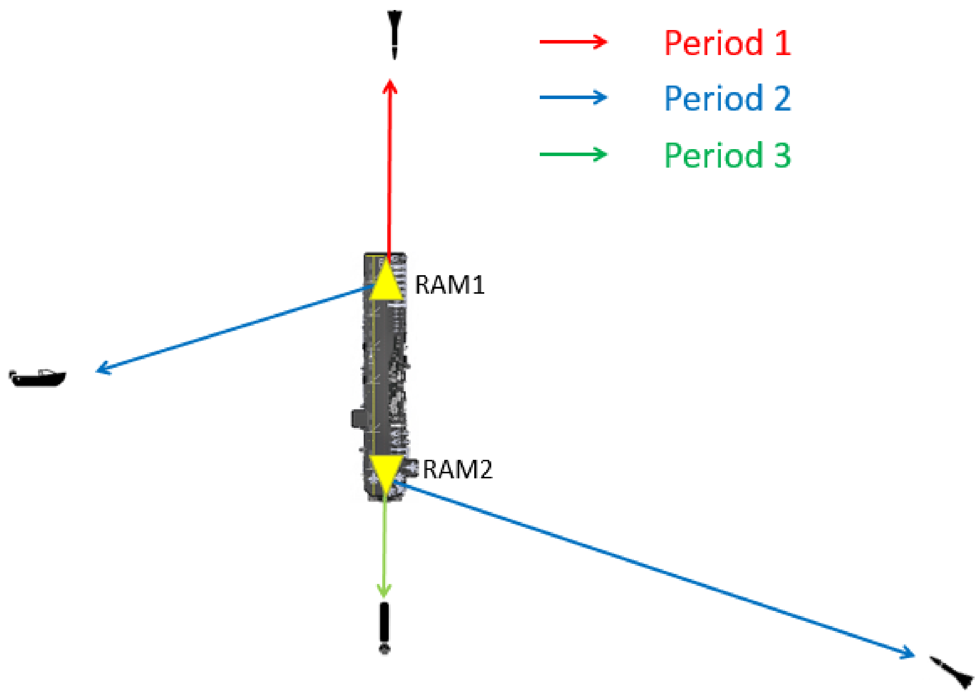
Period 2		
Order	RAM1	RAM2
1	Surf1	Air2
2	--	--
3	--	--
4	--	--

Period 3		
Order	RAM1	RAM2
1	--	Sub1
2	--	--
3	--	--
4	--	--

Test Scenario Assignment Report. Recommended weapon-target pairings for notional test scenario. The pairings are ordered by reward value within each time period (highest reward listed at the top of each period) and are indicative of the recommended engagement order.

In this scenario, the automated pairing tool provides intuitive pairing decisions rapidly. The *Air1* target is identified as the highest priority, as it has the shortest time until impact and poses a high threat to the ship. As this target is feasible in time period 1 it is paired immediately to the *RAM1* weapon system. Similarly, the *Sub1* target was identified as having the longest time until impact, and thus, the greatest available time to engage. Therefore, this target could be assigned to a later time period in order to address more time-sensitive threats. The surface target, *Surf1*, is not itself a threat to the ship; instead, the secondary weapons it is carrying are the primary threat. So, although *Surf1* is relatively far away from the ship, moving at a slow speed, it only has to get within its secondary weapon system firing range to become an extreme threat to the ship. As such, the model pairs it to an available defensive system when prior to it reaching firing range of the ship. A visual depiction of the engagement profile showing the pairings made by time period is shown in Figure 4.

Figure 4. Test Scenario Engagement Profile



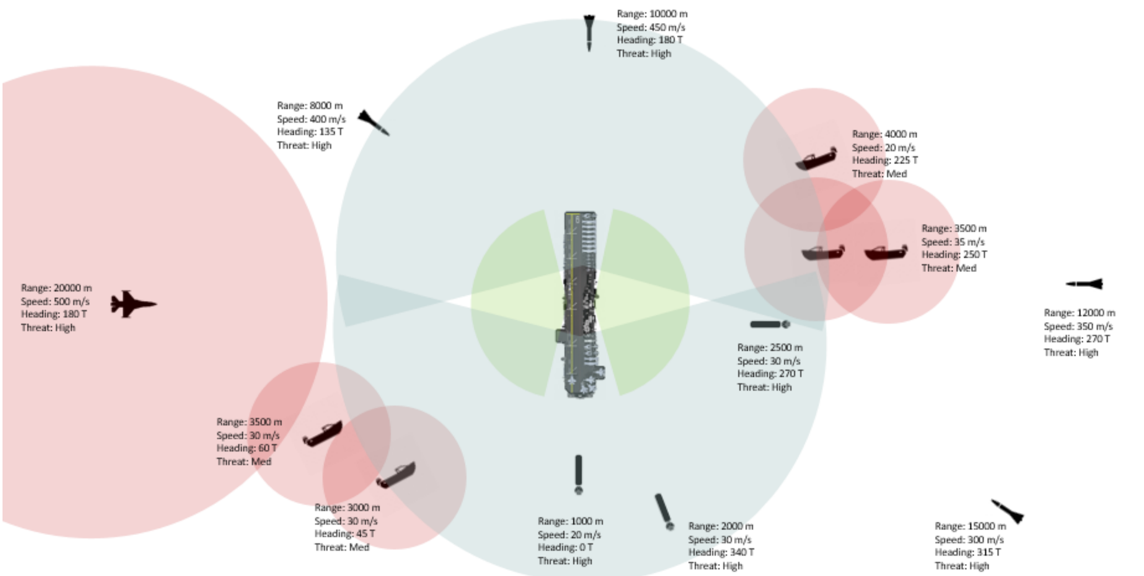
Visualization of Test Scenario Engagement Profile. Weapon-Target pairings are depicted by color-coded lines. Red lines indicate an immediate pairing, while blue and green lines represent pairings recommended for time periods 2 and 3, respectively. Ranges are not to scale.

While *Athena* presents a recognizable solution to an operator, it is important to note that this automation looked at all possible pairings and identified the optimal profile in a very short time. When this scenario was run ten times on a general-purpose laptop, utilizing GAMS with CPLEX, the average time to solve the scenario was approximately two seconds. This time includes all pre-processing calculations (0.17 seconds), optimization (1.89 seconds) and report generation (0.06 seconds).

C. EXPANDED SCENARIO

In order to demonstrate the usefulness and ability of such a system when there are a large number of possible pairings, an expanded test scenario was developed. This scenario equips the same ship with two CIWS self-defense systems along with the RAM launchers used in the previous test scenario. Additionally, the target space has been expanded from 4 targets to 13. A visual depiction of the battlespace is provided in Figure 5. While the previous scenario resulted in 72 possible pairings across the time periods, this scenario results in over 300 possible pairings and depicts how complex the decision-making process can become.

Figure 5. Visual Depiction of Expanded Test Scenario



Visualization of Expanded Test Scenario. Battlespace depiction of a large-deck amphibious assault ship presented with multiple incoming threats spread across multiple domains. Threats in this scenario include 5 air targets (4 missiles, 1 aircraft), 5 surface targets with secondary weapon capabilities and 3 subsurface targets. In this scenario all targets are presented as approaching the ship's locations, however, this is not a requirement of the model. Ranges are not to scale.

As in the previous test example, the RAM platforms are loaded with surface-to-air, surface-to-surface and surface-to-subsurface munitions. The CIWS platforms used in this scenario are depicted as having the capability (i.e., ammunition available) to engage two threats each, either air or surface. Tables 5 and 6 outline the weapon and target characteristics of this test scenario.

Table 5. Expanded Test Scenario Weapon Inputs

Launcher	Submunition	Type	Num Avail	Range (m)	Speed (m/s)	Weap_Heading (degRel)	SwingRate (deg/s)	EnvelopeLo (degRel)	EnvelopeHi (degRel)
RAM1	BlockI	Air	2	15000	700	0	90	260	100
RAM1	Medusa	Surface	2	12000	700	0	90	260	100
RAM1	ATT	Sub	2	10000	30	0	90	260	100
RAM2	BlockI	Air	2	15000	700	180	90	80	280
RAM2	Medusa	Surface	2	12000	700	180	90	80	280
RAM2	ATT	Sub	2	10000	30	180	90	80	280
CIWS1	20mm	Air Surface	2	3500	1000	90	100	0	180
CIWS2	20mm	Air Surface	2	3500	1000	270	100	180	360

Expanded Test Scenario Weapon Inputs. Static weapon system characteristics tab within the model. This table contains the characteristics of the available defensive weapon systems within this test scenario, including the weapon identification, type, available ammunition and capabilities. This scenario includes two RAM launchers with air, surface and subsurface capabilities and two CIWS with air and surface capabilities.

Table 6. Expanded Test Scenario Target Inputs

Primary Weapon System								Secondary Weapon System		
ID	Type	Range (m)	Speed (m/s)	Bearing (deg)	Heading(deg)	P_Hit	Threat	FireRange (m)	P_Hit	Damage
Air1	Air	10000	450	0	180	0.9	3	0	0	0
Air2	Air	15000	300	135	315	0.9	3	0	0	0
Air3	Air	8000	400	315	135	0.9	3	0	0	0
Air4	Air	12000	350	90	270	0.9	3	0	0	0
Air5	Air	20000	500	270	90	0	0	15000	0.9	2
Sub1	Sub	1000	20	180	0	0.9	3	0	0	0
Sub2	Sub	2000	35	160	340	0.9	3	0	0	0
Sub3	Sub	2500	30	90	270	0.9	3	0	0	0
Surf1	Surface	3500	35	70	250	1	0	2000	0.8	2
Surf2	Surface	4000	20	45	225	1	0	2750	0.8	2
Surf3	Surface	3500	35	70	250	1	0	2000	0.8	2
Surf4	Surface	3000	30	225	45	1	0	2000	0.8	2
Surf5	Surface	3500	30	240	60	1	0	2500	0.8	2

Expanded Test Scenario Target Inputs. Static target characteristics tab within the model. This table contains the characteristics of each identified target, including its type, range, bearing and threat index. This test scenario includes 5 air targets, 5 surface targets and 3 subsurface targets.

As previously noted, this expanded scenario greatly grows the possible pairing space. The 312 possible pairing options are reduced during the pre-processing feasibility controls to just 53 feasible pairings before being loaded into the optimization model. The model produced during this test scenario is comprised of 46 constraints and 54 variables, 53 of which are binary and when run on the same general-purpose laptop requires an average solve time of three seconds, a small increase to accommodate the additional 140 possible pairings. Table 7 and Figure 6 outline the assignment results and engagement profile of this expanded scenario, respectively.

Table 7. Expanded Test Scenario Assignment Report

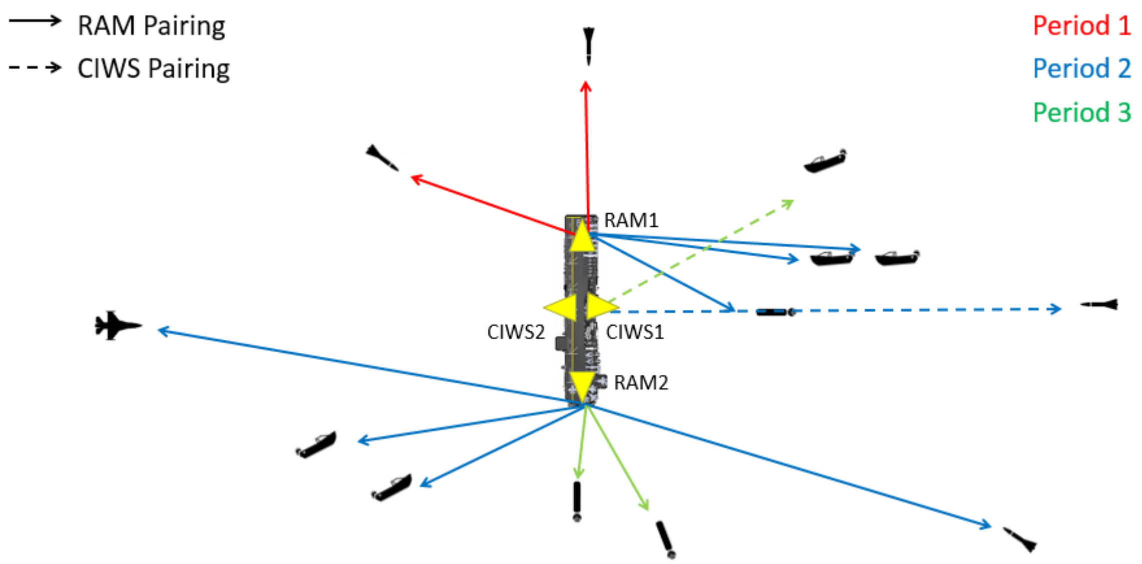
Period 1				
Order	RAM1	RAM2	CIWS1	CIWS2
1	Air3	--	--	--
2	Air1	--	--	--
3	--	--	--	--
4	--	--	--	--
5	--	--	--	--

Period 2				
Order	RAM1	RAM2	CIWS1	CIWS2
1	Sub3	Air2	Air4	--
2	Surf1	Air5	--	--
3	Surf3	Surf5	--	--
4	--	Surf4	--	--
5	--	--	--	--

Period 3				
Order	RAM1	RAM2	CIWS1	CIWS2
1	--	Sub2	Surf2	--
2	--	Sub1	--	--
3	--	--	--	--
4	--	--	--	--
5	--	--	--	--

Expanded Test Scenario Assignments. Recommended weapon-target pairings for expanded test scenario. The pairings are ordered by reward value within each time period (highest reward listed at the top of each period) and are indicative of the recommended engagement order.

Figure 6. Expanded Test Scenario Engagement Profile



Visualization of Expanded Test Scenario Engagement Profile. Weapon-Target pairings are depicted by color-coded and differentiated line segments. Solid line segments represent RAM pairings while dashed lines represent CIWS pairings. Additionally, red lines indicate an immediate pairing while blue and green lines represent pairings recommended for time periods 2 and 3, respectively. Ranges are not to scale.

D. STRESSING SCENARIO

To better understand the capabilities and limitations of the model a test scenario was developed to stress it and determine whether significant solve-time increases occur. This stressed model consisted of 150 incoming targets, broken into equal groups of 50 across the three domains. Target parameters for each type of threat were randomly generated within a type-defined state space. In addition, the available weapon systems were expanded to include 4 RAM launchers and 4 CIWS.

The *Athena* model generates a MIP with over 300 decision variables and is executed using the GAMS/CPLEX model on the same desktop computer. The timing results for all test scenarios conducted, in both GAMS/CPLEX and Pyomo/CBC are provided in Tables 8 and 9, respectively.

Table 8. GAM/CPLEX Runtime Results

Scenario	**Weapon Systems**	**Targets**	**Feasible Pairings**	**Pre-Processing**	**MIP**	**Reporting**	**Total**
Simple	2	4	11	0.17	1.89	0.03	**2.09**
Expanded	4	13	53	0.72	2.26	0.06	**3.04**
Stressed	8	150	357	13.28	1.99	0.50	**15.77**

Timing Results for Example Scenarios. Average time, in seconds, to execute the model in GAMS/CPLEX. Additionally, the pre-processing, MIP and assignment reporting times are individually presented. Reported times are averages of 10 runs. Solve times for the MIP do not increase appreciably, however, pre-processing calculations do increase sharply as the number of possible pairings increases.

Table 9. Pyomo/CBC Runtime Results

Scenario	**Weapon Systems**	**Targets**	**Feasible Pairings**	**Pre-Processing**	**MIP**	**Reporting**	**Total**
Simple	2	4	11	0.16	2.95	0.03	**3.15**
Expanded	4	13	53	0.75	3.57	0.06	**4.38**
Stressed	8	150	357	13.16	4.84	0.49	**18.49**

Timing Results for Example Scenarios. Average time, in seconds, to execute the model in Pyomo/CBC. The GAMS/CPLEX combination is approximately 30% faster than the Pyomo/CBC combination in the simple and expanded scenarios.

V. CONCLUSIONS AND OPPORTUNITIES FOR FURTHER RESEARCH

A. SUMMARY

This decision aid is intended to provide naval operators with a tool to quickly and accurately assess a complicated battlespace and respond to swarming threats. The existing manual process hinders the speed and efficiency of real-time weapon-target pairing in high-threat environments. This tool could be used in an automatic pairing-engagement mode to optimally engage a large number of threats, were systems integration to occur. The use of this model against swarming threats cuts down on operator workload and reduces the kill-chain timeline associated with shipboard defense. Additionally, more weapon-target pairings can be considered with this model than in current manual processes, allowing for a more tailored and optimal defensive engagement.

B. FUTURE DEVELOPMENTS

While this model has shown the ability to provide timely and intuitive solutions to complicated problems, there is still much to be done. First and foremost, *Athena* does require the user to input all data manually through the Microsoft Excel user-interface, a method for data input that clearly renders the system less useful for shipboard defense. Before the model can be used in a defensive engagement, integration with shipboard radar and targeting systems, such as the systems in use aboard the CVN, LHA, LHD and LPD class ships, is essential.

Additionally, in cases such as shipboard defense against multiple threats, solve-time is of the utmost importance. In this regard, any system used for this purpose should be of sufficient speed to deal with multiple threats in real-time. This model was predominately constructed and tested on a general purpose laptop and solved the limited test scenarios in approximately 2 seconds. Implementation on faster, dedicated hardware and software would allow for continuous, real-time assignment.

The most exciting possibility is networking *Athena* with an entire naval defensive group. Were this done, friendly ships could coordinate their defensive efforts against swarming threats. If this model was included on all ships in an operating environment with shared target and weapon data, a coordinated optimization could be conducted in order to produce the optimal defense of *all* ships in the battlespace. The sharing of information would allow ships that are in danger of being overwhelmed by incoming threats to receive support from other ships operating area. This network would create a robust system of self-defense, producing real-time engagement profiles within the battlespace and serving to coordinate the defensive actions of the group.

With regard to the model itself, certain fine-tuning will allow for better weapon-target pairings. System parameters, including the probability of kill, swing rate and munition speed are notional; actual system data should be used for realistic results. Additionally, sensitivity analysis of the weighted parameters within the reward function, such as the free time and priority expressions, would allow the model to better prioritize incoming targets for assignment. Subject matter expert input and modeling and simulation analysis could better identify the critical weighting of these parameters to ensure the best pairings are made in regard to operating environment and mission. Additionally, if this model is to be implemented in a real-time, continuously updated environment a persistence constraint should be added to the optimization formulation. The introduction of a persistence constraint would discourage the model from continuously changing pairing recommendations based on updated information, which may have the effect of complicating the engagement profile. With the inclusion of this constraint, the model would be penalized for changing the pairing profile from one run to the next, and as such, would only do it if it is absolutely necessary. This would serve to ensure the operator gets consistent and coherent pairing recommendations throughout the engagement.

Lastly, this thesis was conducted at the unclassified level in order to ensure full distribution. All figures and data used in the development of this thesis were estimated from open-source information.

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